

Advanced Diagnostics For Developing High-Brightness Electron Beams

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Advanced diagnostics for developing high-brightness electron beams

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Abstract

The production of high-brightness particle beams calls for the development of advanced beam diagnostics. High brightness beams, meaning beams with a high density in phase space, are important for many applications, such as short-wavelength Free-Electron Lasers and advanced accelerator systems. A diagnostic that provides detailed information on the density distribution of the electron bunch in multi-dimensional phase-space is an essential tool for obtaining small emittance at a high charge. This diagnostic system has been developed at Brookhaven National Laboratory. One component of the system is the measurement of a slice emittance which provides a measurement of transverse beam properties (such as emittance) as a function of the longitudinal position. Changing the laser pulse profile of a photocathode RF gun has been suggested as one way to achieve non-linear emittance compensation and improve the brightness and that can be diagnosed by the slice emittance system. The other element of the diagnostic is the tomographic reconstruction of the transverse phase. In our work we give special attention to the accuracy of the phase space reconstruction and present an analysis using a transport line with nine focusing magnets and techniques to control the optical functions and phases. This high precision phase space tomography together with the ability to modify the radial charge distribution of the electron beam presents an opportunity to improve the emittance and apply non-linear radial emittance corrections. Combining the slice emittance and tomography diagnostics leads to an unprecedented visualization of phase space distributions in 5 dimensional phase-space and an opportunity to perform high-order emittance corrections. This should lead to great improvements in the beam brightness.

Introduction

The determination of the electron beam density distribution in multi-dimensional phase-space is accomplished by the combination of two techniques: The slice-emittance measurement which provides the longitudinal information and transverse phase-space tomographic measurement which provides the density distribution in the four transverse dimensions of phase space. Measurement of a slice emittance has been achieved and provided a clear demonstration of the linear longitudinal emittance-compensation scheme [1]. Changing the laser pulse profile of a photocathode RF gun has been suggested as one way to achieve non-linear emittance compensation [2]. The tomographic reconstruction of the phase space was suggested [3] and implemented [4,5] using a single quadrupole scan. In the present work we give special attention to the accuracy of the phase space reconstruction and present an analysis using a transport line with nine focusing magnets and techniques to control the optical functions and phases. This high precision phase space tomography together with the ability to modify the radial charge distribution of the electron beam presents an opportunity to improve the emittance and apply non-linear radial emittance corrections. When we combine the slice emittance and tomography diagnostics, we obtain an unprecedented visualization of the density distribution in 5 dimensional phase-space. We also generate an opportunity to perform high-order emittance corrections.

The Experimental Setup

The schematic layout of the ATF acceleration and transport lines that were used in the slice emittance measurement and the tomographic reconstruction is presented in Figure 1.

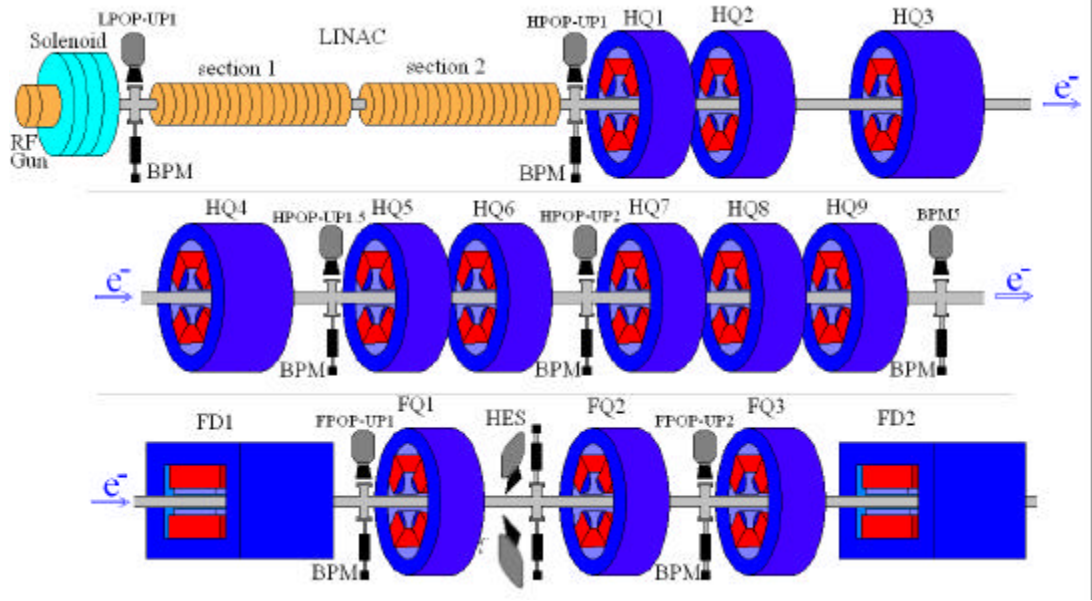


Figure 1. Schematic layout of the ATF accelerator system components used in the slice emittance measurement and the tomographic analysis.

In the naming convention of ATF elements, the first letter designated a particular straight beam line between bending dipoles, followed by letter(s) designating the type of element, followed by a number, increasing along the beam direction. Thus the H beam line (between the linac and the first dipole HD1) had quadrupole lenses HQ1 through HQ9, pop-up phosphor screen beam distribution monitors HPOP-UP1 through HPOP-UP 2, etc. The beam is generated at the photocathode by a 10 ps long UV laser pulse. A linear emittance compensation solenoid is located right after the RF gun controls the phase space distribution of the electron beam. Two RF linac sections with independent phase control accelerate beam from 5 MeV to approximately 50 MeV. The phase of the second section is controlled independently by a motor controlled phase shifter. The H straight line with nine quadrupoles (HQ1 to HQ9) was used to generate rotations (phase advance) without a change in the beam size (constant optical functions). A beam profile monitor (BPM5) was used to measure the projection. The tomographic recovery procedure determines the phase space distribution at HPOP-UP1. The high energy beam is bent horizontally by a 20 degrees dipole magnet and a small slice in energy may be selected by a variable aperture slit. Additional beam diagnostics, located downstream of the slit provide charge and profile information.

Slice emittance measurement

We perform the “Slice Emittance” measurement by dissecting the electron bunch longitudinally into slices on a picosecond time scale. The emittance and orientation of the phase space ellipse are measured for each individual slice.

The second linac section, dipole and slit form a “Slice Filter” that passes only a short slice of the beam pulse downstream of the slit. The quadrupole lenses and beam profile monitor downstream of the filter form an analyzer to measure the beam matrix of the slice. The filter is tuned to a given slice by changing the phase of the second linac section. Since the dipole current is constant, the energy of a selected slice is constant regardless of its position along the bunch, and the optics of the selected slices in the filter (and before it) is identical.

The longitudinal charge distribution of the electron beam bunch was measured by taking the charge passed by the Slice Filter as a function of phase. Three slices were selected for the slice emittance measurement, one near the leading edge of the beam pulse (with the highest peak current), one near the center and one near the end (with the lowest peak current). The slice phase space evolution depends on its current and its position in the bunch, but we have avoided the steep leading edge of the bunch because of the sensitivity to timing jitter at that point. For each solenoid field setting, the vertical beam size was measured as the function of the scanning quadrupole magnet current. The beam matrix at the entrance of the quadrupole represents three parameters that are the variables in a best fit procedure to the vertical size as a function of current.

In Figure 2 we show the fitted beam ellipses of the slices. To illustrate the relative orientation between the slice ellipses, they were rotated with a known transfer matrix so that the phase space ellipse of the end slice is an erect ellipse and has a fixed beam size in each of the plots. Figure 2 shows only the relative rotation of the slice ellipses. The best emittance compensation is achieved when the solenoid current is adjusted such that all the slice ellipses line up. This will reduce the emittance of the whole electron bunch by producing the smallest projected area, with summation weighted by the charge in each slice.

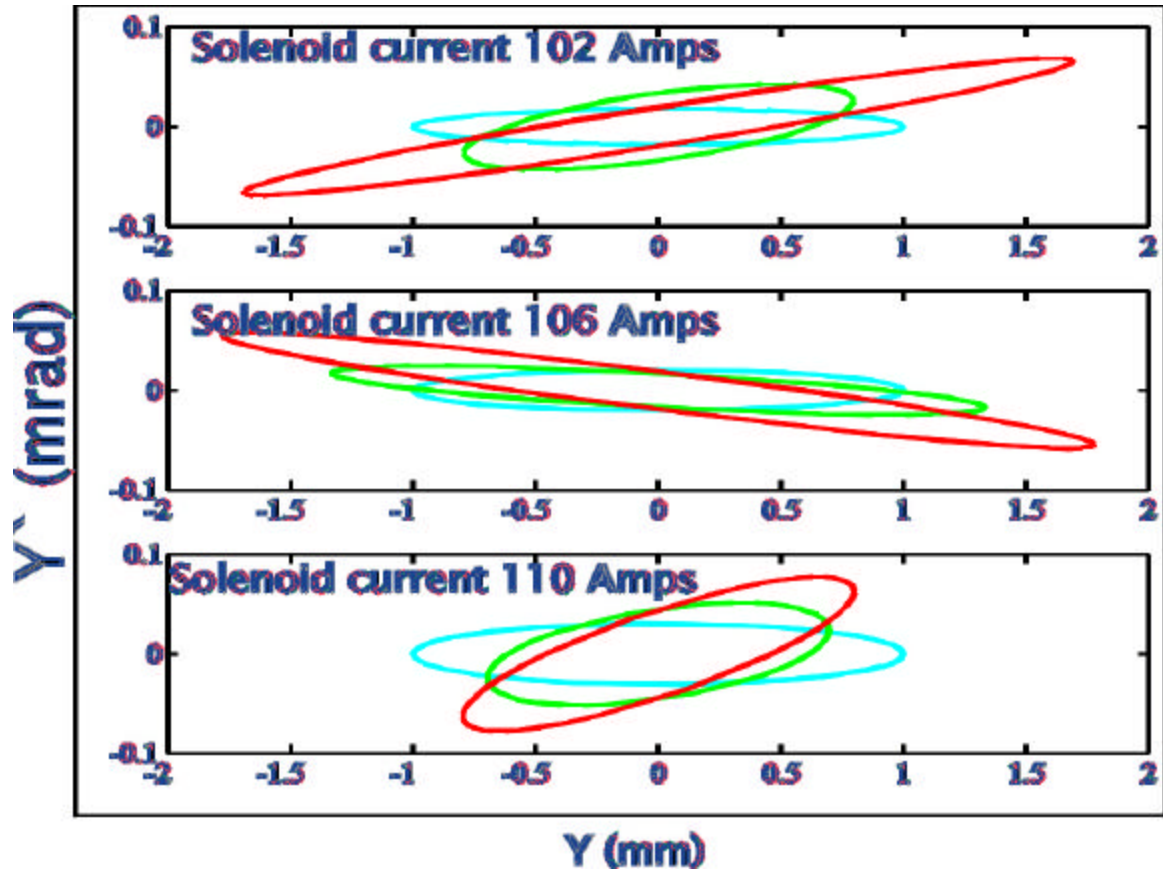


Figure 2. Plots of the transverse phase space ellipses for each slice. The solenoid currents are:
a) 102 A, b) 106 A, c) 110 A

Tomographic recovery

Tomography is the technique of reconstructing an object from its projections. In the Physics of beams one can use tomographic techniques to reconstruct a beam density distribution in phase space using its projections in real space. In other words, the images of a beam on a phosphorescent screen (taken, for example, by a CCD camera) can be used to derive the phase-space density-distribution. In order to do that, we must be able to rotate the distribution in phase space to generate independent projections on the screen. This is done by changing the beam transport matrix, using variable strength lenses.

In order to establish the quality of the tomographic recovery procedure, a special program based on Mathcad was developed. Some of the issues studied were the tolerances for angular and stretching errors in the focusing channel, the required number of measured projections, the effect of smoothening during recovery and more. We concluded that in order to recover features that are about one tenth of the distribution size we should measure 32 evenly space projections and the rotation phase and stretch errors should be of the order of 10% or less.

Computer control system

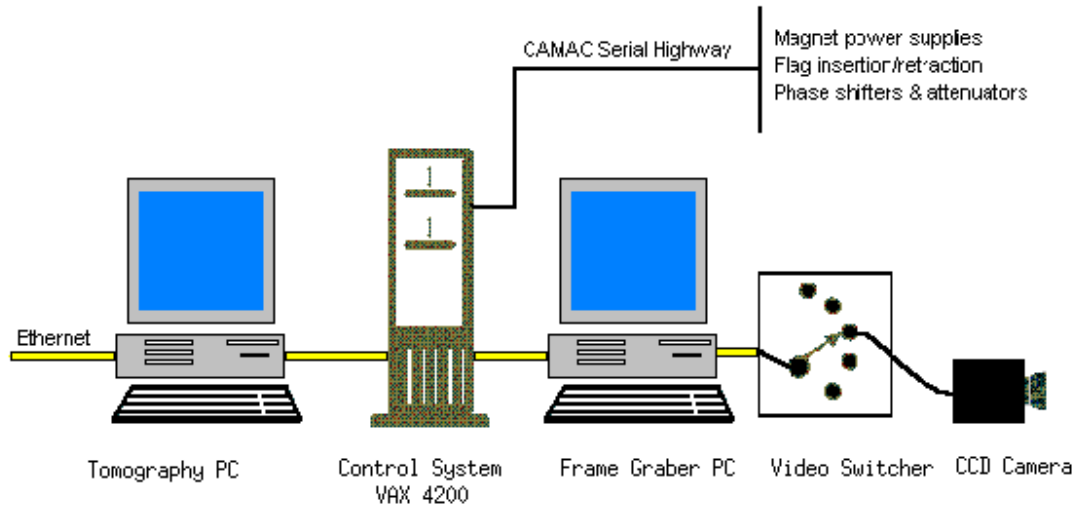


Figure 3. Schematic layout of the ATF control systems associated with the tomography program.

The beam tomography application uses three subsystems of the Accelerator Test Facility's computer network: 1) the main control system and its peripherals, 2) a PC-based video frame grabber and 3) an additional PC on which the tomography application code resides. Figure 4 shows a schematic representation of the hardware used in this project.

A brief description of each of these subsystems follows:

- **Main Computer Control System**

The central control computer, a Digital VAX 4200, is configured with a CAMAC serial highway driver connected directly to its backplane. Six CAMAC crates are located at several positions around the ATF complex, each equipped with interface cards to control and monitor the facility's various devices, including magnetic optics components and beam diagnostics. Vsystem, a commercial software tool package, is used to construct operator displays, generate the underlying database and provide an interface for applications programs. In addition to the main system, other computers are networked over a local area Ethernet.

- **PC-based Video Frame Grabber**

Video frame analysis is the primary measurement technique used in this application. A PC-based frame grabber system was built using components from the Imaging Technology's MVC 150/40 family. By combining their video motherboard card and several plug-in modules, a complete, high-performance, pipelined video image processor occupying 2 PCI slots was constructed. The plug-ins include a variable scan video acquisition and 8-bit digitizer and a series of computation modules: an arithmetic unit, a convolution and logic unit, a histogram, projection and feature extraction unit and a video memory. Most computations and projections are developed locally in this dedicated arithmetic hardware where all modules can communicate over their own local bus, thus placing no serious burden on the host PC. Frame grabbing, digitization and display are all completely synchronous with each pulse of the electron beam. Programming to control this subsystem was done using Microsoft Visual C++ under Windows NT. It can operate either as a stand-alone instrument (setup and results displayed on a local

monitor) or as a slave device where commands and data are exchanged over a network TCP socket connection.

- **Tomography Application PC**

The tomography computer holds and executes all the actual logic needed to carry out a measurement. Like the frame grabber PC, it was also programmed using Visual C++ under Windows NT. Its program, called "TOMO", orchestrates the step-by-step actions needed to complete a measurement sequence, directing the main control VAX to manage facility hardware on its behalf. In this sense, the main control computer and the frame grabber PC are slave devices to the tomography PC. Once authorized, the tomography application has complete access to the accelerator database. By sending and receiving socket messages, values can be written to or read from the database, in turn signaling detached server processes to implement the desired action. These messages and acknowledgments mimic the actions a human operator would follow in making a measurement: setting and verifying magnet current, inserting and retracting beam profile monitors, switching video cameras to the frame grabber, requesting image statistics and projections, etc. The interface of the program "TOMO" reflects all the operations that are implemented in the software.

The tomographic measurement can be broken into a few steps [6].

1. The first step of the tomographic analysis is a measurement of the initial conditions of the electron beam at the linac's exit. The variation of the beam size as a function of current in the first triplet is used to match the optical functions in two directions. In the first step, the graphics window shows the beam size in the X and Y planes as a function of the triplet current. One can observe the fluctuations of the beam size and get a measure of the stability of the system.
2. In the second step, we calculate tunes for the just-measured initial conditions of the beam. A simplex method is used to match the required phase advance and keep the electron-beam conditions at the end of the transport line nearly constant. At this stage, the graphical window shows the variation of the optical functions vs. position along the transport line for each selected value of the phase advance.
3. The third step is to measure the beam projections for the tunes calculated in the previous step. The graphics output window shows the measured projections in the X and Y planes for a particular tune.
4. In the last step we reconstruct the phase space distribution from the measured projections. In this step the graphics window presents the recovered distribution in X-X' and Y-Y' phase spaces.

The tomographic reconstruction of transverse phase space may be combined with the measurement of a longitudinal slice [1], to produce the transverse phase space distribution of a longitudinal slice [5]. This leads to a measurement of the 5 dimensional phase space density distribution in (X, P_x , Y, P_y , Z). For this purpose we replace the quadrupole scan emittance measurement by a tomographic analysis of the slice. Tomographic measurements of a slice may be done at FPOP-UP2 in the Y-Y' plane, or in one of the experiment hall beam lines downstream of another dipole (e.g. FD2), which are dispersion free.

Control of the phase-space density-distribution

The laser photocathode RF gun presents a unique platform to the study and manipulation of the electron beam distribution in phase space. This can be done by shaping the laser intensity profile, thus shaping the

electron beam charge distribution. This may lead to non-linear emittance corrections, and to possible improvements in the brightness of electron guns.

We generated three laser radial profiles: The natural Gaussian distribution, and increased flatness (nearly uniform) profile and an annular profile. These three profiles were used in the electron-beam tomography-measurements and they demonstrate the effect of laser intensity profiles on the beam phase space. In the following three figures we present the laser transverse distribution, electron beam transverse distribution and tomographic recovery of the electron beam phase space for the three laser intensity distributions.

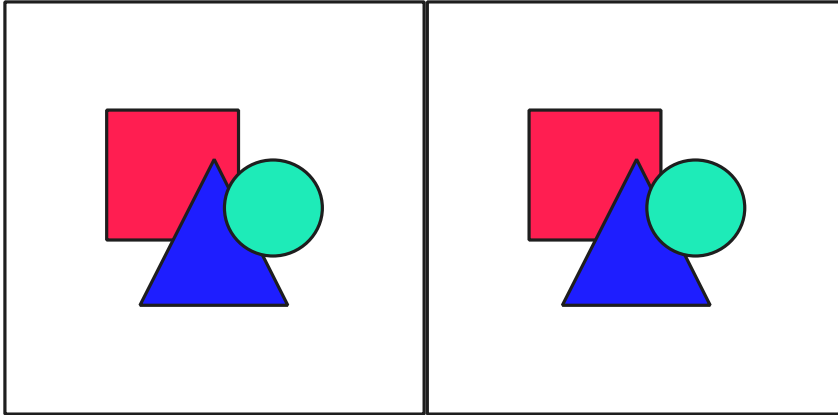


Figure 4. Gaussian derived directly from the laser output. Left: The laser intensity profile. Right: The tomographic recovery of the electron beam's transverse phase space.

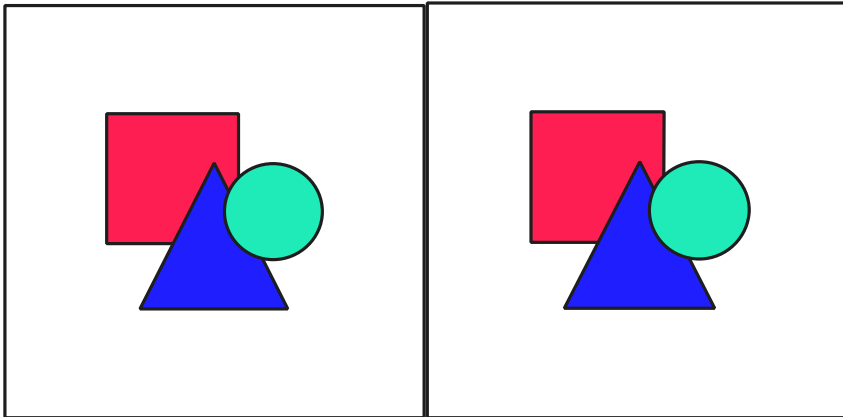


Figure 5. Gaussian with increased flatness. Left: The laser intensity profile. Right: The tomographic recovery of the electron beam's transverse phase space.

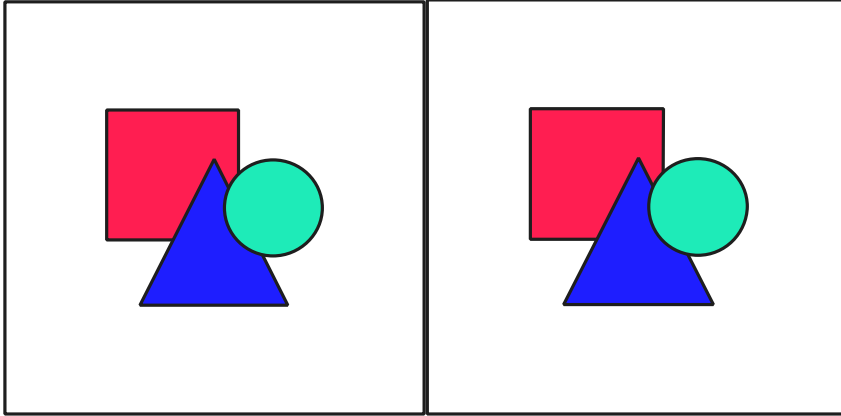


Figure 6. “Donut” laser distribution. Left: The laser intensity profile. Right: The tomographic recovery of the electron beam’s transverse phase space.

The tomographic analysis demonstrates clearly that the Gaussian with increased flatness presents the best beam brightness (the smallest area in transverse phase space) of the three measured distributions. The beam intensity used in these measurements was not so large that significant phase space distortion would be expected for a nearly flat radial charge distribution. In future experiments we will study higher beam charges and attempt to correct the emittance by modifying the charge distribution – a non-linear emittance correction.

Acknowledgments

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